Connecting Dark Matter and the LHC in the Dual Probes of Physics Beyond the SM

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Focus of this Talk

- After the LHC data begins to comes in, it is expected to have a major impact on Particle Physics models, and in particular, the impact will effect those models which predict the presence of Dark Matter.

- Thus, in this talk I will focus on the connection between the expected LHC Signals of new physics, the complimentary constraints from the Tevatron, and several signals of new physics relevant for Dark Matter detection experiments.

The Flow

- Introduction: Connecting Colliders and Cosmology
- Decoding the Origin of Dark Matter using LHC data
- Sparticle mass hierarchies and the LHC
- General LHC Signatures & Dark Matter Direct Detection

[If time permits]

- New Possibilities for Dark Matter, implications for the Tevatron and the LHC, & the PAMELA Experiment.

Conclusions: Looking ahead

LHC Signatures and Dark Matter Signatures

- Over the last decade, or so, there has been a highly concentrated effort to map out the **parameter space** of SUSY models consistent with WMAP constraints, with constraints from FCNC, sparticle mass limits etc . . . ("the consistent parameter space" - hundreds of papers).

- However, recently it has become possible to extend "the consistent parameter space" analysis to make actual predictions at the LHC and map out the space of possible **LHC signatures**.

- Further, the space of signatures is <u>not</u> limited to only **collider signatures** . It is also of importance to connect these signatures of new physics of underlying models with **astrophysical signatures**, in particular, in the context of **Dark Matter**.

Physics beyond the Standard Model ... Many Models

- Compositeness
- SUSY/SUGRA + GUTS , Strings and Branes
- Extra (warped) dimensions
- Stueckelberg and other $U(1)$ extensions
- Unparticles,...

Is there an underlying fundamental theme here ... ?

Physics beyond the Standard Model

★ **Many models of Physics BSM require a Hidden Sector**

- SUSY/SUGRA + GUTS, Strings + Branes
  [Soft Breaking in the Hidden Sector]
- Extra (warped) dimensions
  [Hidden Planck Brane $\Longleftrightarrow$ TeV Scale Brane]
  or [Compactified EDs]
- Stueckelberg and other $U(1)$ extensions
  [Hidden $U(1)s$]
- Unparticles, Ungravity
  [Higher Dimensional Operators from Hidden Sector]

LHC Signatures and Dark Matter Signatures

- Whatever the model of interest, the endpoint of any analysis is a collection **photons + leptons + jets + missing energy**.

- There are many possible models of new physics.

- From these one must **reconstruct** the underlying model of new physics in order to understand what it is we are seeing in the detectors.

- At the same time, in many models there are good candidates for cold dark matter.

- We the increasing precision of **Dark Matter detection experiments** we must be equally prepared to understand what we observe from these detectors.

From Models to LHC signals

- It is important to investigate a wide array of possible channels where new physics may arise.

- LHC Signatures break up into two classes:
  (a) Counting of Event Rates - (no. of events in each channel)
  (b) Kinematical Distributions -(looking for peaks and edges)

- We have analyzed LHC Event Rates in 40+ channels and a collection of Kinematical Distributions, and we have found that it is possible, in many cases, to determine which model we are observing with various LHC signatures.

- Resolution of the parameter space $\Longleftrightarrow$ signature space is possible even in cases that first glance would seem very difficult.

Event Rates in 40 Channels

| Signature	Description	Signature	Description
0L	0 Lepton	0T	0τ
1L	1 Lepton	1T	1τ
2L	2 Leptons	2T	2τ
3L	3 Leptons	3T	3τ
4L	4 Leptons and more	4T	4τ and more
0L1b	0 Lepton + 1 b-jet	0T1b	0τ + 1 b-jet
1L1b	1 Lepton + 1 b-jet	1T1b	1τ + 1 b-jet
2L1b	2 Leptons + 1 b-jet	2T1b	2τ + 1 b-jet
0L2b	0 Lepton + 2 b-jets	0T2b	0τ + 2 b-jets
1L2b	1 Lepton + 2 b-jets	1T2b	1τ + 2 b-jets
2L2b	2 Leptons + 2 b-jets	2T2b	2τ + 2 b-jets
ep	e^+ in 1L	em	e^- in 1L
mp	μ^+ in 1L	mm	μ^- in 1L
tp	τ^+ in 1T	tm	τ^- in 1T
OS	Opposite Sign Di-Leptons	0b	0 b-jet
SS	Same Sign Di-Leptons	1b	1 b-jet
OSSF	Opposite Sign Same Flavor Di-Leptons	2b	2 b-jets
SSSF	Same Sign Same Flavor Di-Leptons	3b	3 b-jets
OST	Opposite Sign Di-τ	4b	4 b-jets and more
SST	Same Sign Di-τ	TL	1τ plus 1 Lepton

Table: A list of **40 counting signatures** investigated; $L = e, \mu$ signifies only electrons and muons. In each channel listed $(+jets + P_T^{\mathrm{miss}})$ is implied.

How Good is our Simulations?
Pretty, Pretty, Pretty Good (PGS4)
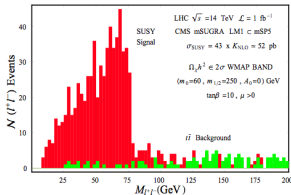
OUR SIMULATION WITH PGS
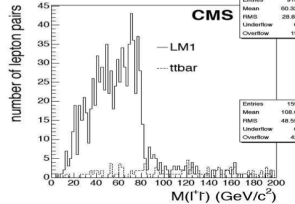
CMS EXPERIMENTAL GROUP LHC SIMULATION

M. Chiorboli, M. Galanti, A. Tricomi, CMS NOTE 2006/133

Signal and backgrounds also checked with: D. J. Mangeol, U. Goerlach, CMS NOTE 2006/096

Di-lepton distribution LM9 has been reproduced ; W. de Boer, et. al, CMS NOTE 2006/113

Kinematical signatures
1. P_T^{miss} = missing transverse momentum
2. Effective Mass = $P_T^{miss} + \sum_j P_T^j$
3. Invariant Mass of all jets
4. Invariant Mass of e^+e^- pair
5. Invariant Mass of $\mu^+\mu^-$ pair
6. Invariant Mass of $\tau^+\tau^-$ pair

Dark Matter and the LHC

Focus on high scale models, specifically SUGRA GUT models:

- Gauge coupling unification manifest at a high Scale
- Naturally incorporate gravity (SUGRA) by gauging global SUSY ; SUSY breaking in hidden sector (neutral scalars here)
- Dynamic triggering of the Spontaneous Breaking of electroweak symmetry through RGE
- Provide a framework for String and D-Brane model building
- And as a bonus, the number of free parameters is minimized drastically

Recent analyses discussed here:
Daniel Feldman, Zuowei Liu, Pran Nath

- Phys.Rev.Lett.99:251802,2007
- Phys.Lett.B662:190-198,2008
- JHEP 0804:054,2008
- Phys.Rev.D78:083523,2008

Using the LHC to Decode the underlying Mechanism for Dark Matter Production

- LHC data can allow one to decode the mechanism by which dark matter was generated in the early universe in supersymmetric theories.

- WMAP and Current collider data from Tevatron and LEP Experiments Provide important constraints.

- I will focus here on SUSY DM (see ex: Jungman, Kamionkowski, Griest, Phys.Rept.267:195-373,199) and for a modern review of SUSY DM and other DM possibilities see: (G. Bertone, D. Hooper, J. Silk , Phys.Rept.405:279-390,2005).

The two major mechanisms for generation of dark matter :
Stau-Co and the HB/FP & Thermal Annihilations

- Stau Coannihilation (Stau-Co) (**Bino Branch**)

$$\tilde{\tau}\widetilde{\chi}_1^0 \rightarrow (\tau Z), (\tau h), (\tau\gamma)$$
$$\tilde{\tau}\tilde{\tau}^* \rightarrow (f_i\bar{f}_i), (WW), (ZZ), (\gamma Z), (\gamma\gamma)$$
$$\tilde{\tau}\tilde{\tau} \rightarrow \tau\tau$$
$$\tilde{\tau}\widetilde{\ell}_i(i \neq \tau) \rightarrow \tau\ell_i.$$

- Hyperbolic Branch/Focus Point (HB/FP) (**Higgsino Branch**)

$$\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \rightarrow (WW), (ZZ), (t\bar{t}), (b\bar{b})$$
$$\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \rightarrow b\bar{b}, \tau\bar{\tau} \text{ larger bino comp.}$$

- A study of the **SUSY signatures reveals several correlated smoking gun signals** allowing a clear **discrimination between the Bino and the Higgsino branches** which are responsible for dark matter annhilations in the early universe.

Feldman, Liu, Nath: arXiv:0808.1595, Phys. Rev. D 78, 083523 (2008)
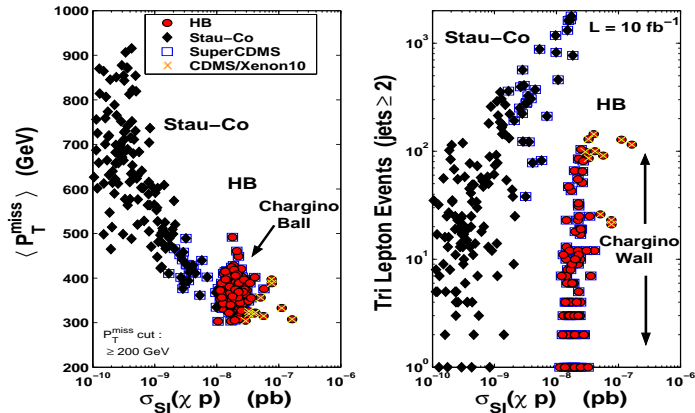
Figure: Right panel: An exhibition of the trileptonic signal vs $\sigma_{\chi p}^{\rm SI}$. Points in the vertical region to the right constitute the Chargino Wall. Left panel: an exhibition of $\langle P_T^{miss} \rangle$ vs $\sigma_{\chi p}^{\rm SI}$. The cluster of points at the end to the right constitute the Chargino Ball. The CDMS/Xe10 constraints (Ahmed:2008 etal) and constraints expected from SuperCDMS (Schnee:2005 etal) are also shown.

- On the CW one typically has $m_H^2 \gg m_h^2$,
- $\sin\alpha \approx \alpha$ where α is the Higgs mixing parameter which enters in the diagonalization of the CP even Higgs mass^2 matrix, and further $\alpha \times \tan\beta \simeq -1$.
- Further, the sfermion poles can be neglected as they make a small contribution in this region.
- in the absence of CP phases we obtain

$$\sigma_{\chi p}^{\mathrm{SI}}(\mathrm{WALL}) \sim C_{\mathrm{SM}}(g_Y n_1 - g_2 n_2)^2 (n_4 + \alpha n_3)^2 (9 f_p + 2 f_{pG})^2 \quad (1)$$

$$\widetilde{\chi}_1^0 = n_1 \tilde{B} + n_2 \tilde{W} + n_3 \tilde{H}_1 + n_4 \tilde{H}_2 \quad (2)$$

$$C_{\mathrm{SM}} = \frac{m_p^2 \mu_{\chi p}^2 g_2^2}{324 \pi m_h^4 M_W^2} \quad (3)$$

The typical ranges for n_i on the wall are: $n_1 \in (.85, .99)$, $n_2 \ll n_1$, and $n_3 \in (.1, .6) \sim -\mathcal{O}(n_4)$. Using numerical values of f_p, f_{pG} one gets $\sigma_{\chi p}^{\mathrm{SI}}(\mathrm{WALL}) \sim 2 \times 10^{-8}$[pb].

Dark Matter and Collider Synthesis

- Models on the **Chargino Wall** have longer decay chains controlled by successive 3 Body decays with more final state particles and thus the missing energy carried by the neutrals is depleted leading to missing P_T^{miss} which is more SM like.

- Conversely Sparticles arising from the **Stau-Co** have much shorter decay chains resulting in fewer final particles and thus the missing energy can get large.

- Since every event carries missing energy, one may examine N_{SUSY} and P_T^{miss} to discriminate amongst the 2 **mechanisms for generation of Dark Matter**.

Feldman, Liu, Nath: arXiv:0808.1595, Phys. Rev. D 78, 083523 (2008)
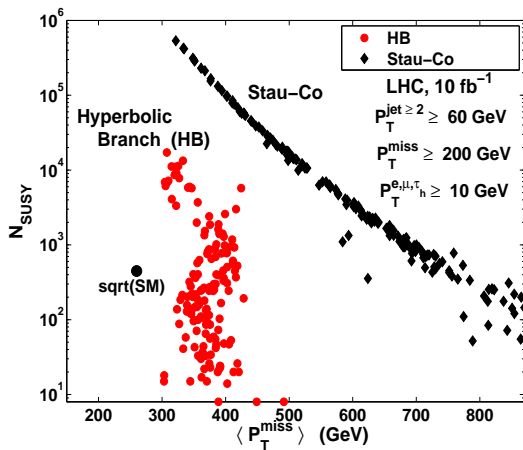
Figure: N_{SUSY} vs. $\langle P_T^{\text{miss}} \rangle$ for each parameter point in the Stau-Co and HB/FP. $\langle P_T^{\text{miss}} \rangle$ acts as an indicator of Stau-Co and and annihilation on the HB/FP.
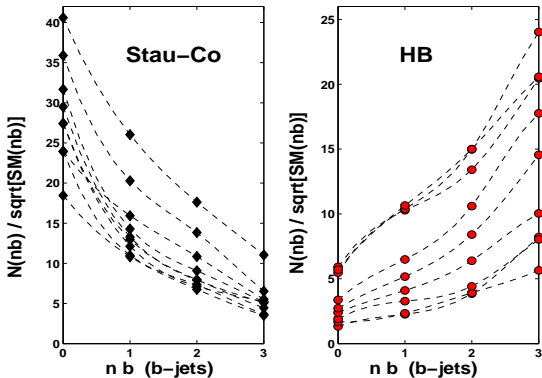
Figure: $N(nb)/\sqrt{\mathrm{SM}(nb)}$ vs nb for the Stau-Co and HB/FP regions where $N(nb)$ ($\mathrm{SM}(nb)$) is the number of SUSY (SM) events that contain n b-tagged jets. A sharp discrimination between the Stau-Co and the HB/FP by b-tagging is observed. The number n_{jet}^* is fixed at 2. Here $m_{\tilde{g}} \leq 1.1$ TeV.

Dark Matter and Collider Synthesis

- On the Chargino Wall (CW) [typical case]:
  - $pp \to (\widetilde{g}\widetilde{g}/\widetilde{\chi}_2^0\widetilde{\chi}_1^\pm/\widetilde{\chi}_1^\pm\widetilde{\chi}_1^\mp)$ are dominant.
  - Contribution from $pp \to \widetilde{g}\widetilde{g}$ enhanced.
  - Squarks are heavy, their production is suppressed.
  - The three body decays of the $\widetilde{g}$ open up - they go dominantly in $b\bar{b} + \chi_i^0$ and $b\bar{t} + \chi_j^+ + \text{h.c.}$.
  - Thus while the CW is rich in b quarks, as mentioned previously, one needs several 3 body decays to get to LSPs.

- Due to Stau-Co [a typical case]
  - $pp \to \widetilde{g}\widetilde{g}$ is more suppressed.
  - Typically get contributions from $pp \to (\widetilde{g}\widetilde{q}, \widetilde{q}\widetilde{q})$.
  - The two body decays of the $\widetilde{g}$ into b quarks are suppressed relative to the CW (though $\widetilde{g} \to \tilde{\bar{b}}_i + b \sim 5\%$), while $\tilde{q}_R \to \widetilde{\chi}_1^0 + q_R$ can be 100%.
  - While a large no. of b jets can still be produced as the no. of events which pass the cuts are larger, $b-$jets are produced proportionally less so, with lower multiplicity than on the CW.
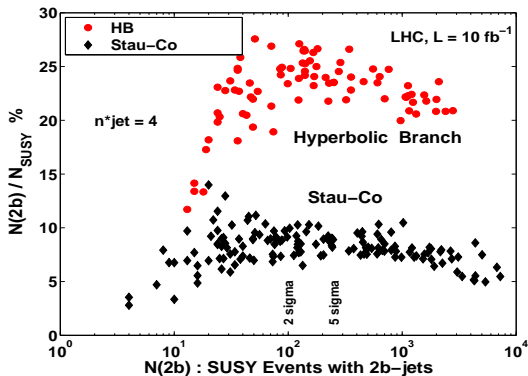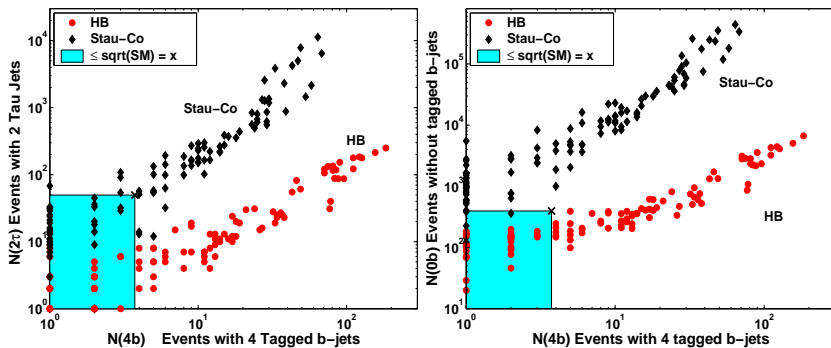
Feldman, Liu, Nath: arXiv:0808.1595, Phys. Rev. D 78, 083523 (2008)

Figure: A plot of $N(2b)/N_{\mathrm{SUSY}}$ vs $N(2b)$ where n^*_{jet} is fixed at 4.

Feldman, Liu, Nath: arXiv:0808.1595, Phys. Rev. D 78, 083523 (2008)

Figure: $N(2\tau)$ (the number of events with two hadronically decaying τ-jets) vs $N(4b)$ (the number of events with 4 tagged-b jets) (Left panel). A similar plot with $N(2\tau)$ replaced by $N(0b)$ (the number of events with no tagged b-jets) (Right panel).

Can the Tevatron and LHC Decode the Underlying Mechanism for Dark Matter Production more Generally?

- We have shown Stau-Co and HB/FP can be separated with the LHC and the mechanism for Dark matter production in the Early Universe and the cause of REWSB can be understood.

- Pole Regions Harder to disentangle

- However we can glean significant information from :
  - Flavor Physics
  - SUSY Higgs Production
  - Collider Production and Mass Splittings
  - Dark Matter Direct Detection

A very useful technique in understanding and sorting out SUSY at the LHC is a study of the possible **sparticle mass hierarchies** that can arise.

Sparticle Mass Hierarchies

- There are 32 sparticle masses in MSSM. Including the constraints of sum rules one has in excess of 10^{25} mass hierarchies. Only one of these would be realized at the LHC if the msugra or some variant is right.

- We focus on the first four sparticle mass hierarchies. A mapping of the parameter space of mSUGRA under constraints from experiment reduces more than 10^4 4 particle hierarchies to very few minimal sugra patterns ($mSPs$)

$$(\mathbf{mSP1 - mSP16}), \quad \mu > 0,$$

$$(\mathbf{mSP17 - mSP22}), \quad \mu < 0.$$

- A similar mapping of NUSUGRA shows 'saturation' with 15 additional NUSUGRA patterns ($\mathbf{NUSP1 - NUSP15}$).

Sparticle Mass Hierarchies

mSP	Mass Pattern	$\mu+$	$\mu-$
mSP1	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{\chi}_3^0$	Y	Y
mSP2	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < A/H$	Y	Y
mSP3	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{\tau}_1$	Y	Y
mSP4	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{g}$	Y	Y
mSP5	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\nu}_\tau$	Y	Y
mSP6	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0$	Y	Y
mSP7	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\chi}_1^\pm$	Y	Y
mSP8	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < A \sim H$	Y	Y
mSP9	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < A/H$	Y	Y
mSP10	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < \widetilde{l}_R$	Y	
mSP11	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0$	Y	Y
mSP12	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{\chi}_1^\pm$	Y	Y
mSP13	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{l}_R$	Y	Y
mSP14	$\widetilde{\chi}_1^0 < A \sim H < H^\pm$	Y	
mSP15	$\widetilde{\chi}_1^0 < A \sim H < \widetilde{\chi}_1^\pm$	Y	
mSP16	$\widetilde{\chi}_1^0 < A \sim H < \widetilde{\tau}_1$	Y	
mSP17	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^\pm$		Y
mSP18	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{t}_1$		Y
mSP19	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < \widetilde{\chi}_1^\pm$		Y
mSP20	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^\pm$		Y
mSP21	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{\chi}_2^0$		Y
mSP22	$\widetilde{\chi}_1^0 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^\pm < \widetilde{g}$		Y

NUSP	Mass Pattern	NU3	NUG
NUSP1	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{t}_1$	Y	Y
NUSP2	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < A \sim H$	Y	
NUSP3	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\tau}_1 < \widetilde{\chi}_2^0$		Y
NUSP4	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\tau}_1 < \widetilde{l}_R$		Y
NUSP5	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau < \widetilde{\tau}_2$	Y	
NUSP6	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau < \widetilde{\chi}_1^\pm$	Y	
NUSP7	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < A/H$		Y
NUSP8	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\nu}_\mu$		Y
NUSP9	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\chi}_1^\pm < \widetilde{l}_R$		Y
NUSP10	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{g} < \widetilde{\chi}_1^\pm$		Y
NUSP11	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < A \sim H$		Y
NUSP12	$\widetilde{\chi}_1^0 < A \sim H < \widetilde{g}$		Y
NUSP13	$\widetilde{\chi}_1^0 < \widetilde{g} < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0$		Y
NUSP14	$\widetilde{\chi}_1^0 < \widetilde{g} < \widetilde{t}_1 < \widetilde{\chi}_1^\pm$		Y
NUSP15	$\widetilde{\chi}_1^0 < \widetilde{g} < A \sim H$		Y

mSP distributions
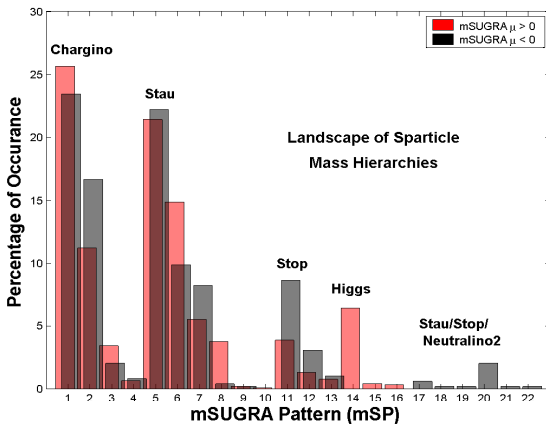
Comparison Between mSP and other Benchmarks

D. Feldman, Z. Liu and P. Nath, Phys. Rev. Lett. **99**, 251802 (2007)

D. Feldman, Z. Liu and P. Nath, JHEP **0804**, 054 (2008)

Snowmass	mSP	Post-WMAP3	mSP
SPS1a, SPS1b, SPS5	mSP7	$A', B', C', D', G', H', J', M'$	mSP5
SPS2	mSP1	I', L'	mSP7
SPS3	mSP5	E'	mSP1
SPS4, SPS6	mSP3	K'	mSP6

CMS LM/HM	mSP
LM1, LM6, HM1	mSP5
LM2, LM5, HM2	mSP7
LM3, LM7, LM8, LM9, LM10, HM4	mSP1
LM4, HM3	mSP3

Table: Mapping between the mSPs and the Snowmass, Post-WMAP3, and CMS benchmark points.

ONLY 5 Mass Patterns Covered in Previous Benchmarks

Some Other Recent Analyses

- We have also recently analyzed independent data sets from Allanach et. al and have found all our mSPs with a similar frequency (data provided from the analysis of : **B. Allanach, K. Cranmer, C Lester, A. Weber**, JHEP 0708:023,2007)

- Recently (last week) an analysis based on the mSP concept in the pMSSM (19 pars) appeared (**C.F. Berger, J.S. Gainer, J.L. Hewett, T.G. Rizzo** e-Print: arXiv:0812.0980)
    - The frequency of mSPs in the pMSSM is quite different than in mSUGRA, though all but one mSP is present in their analysis (saturation not yet achieved).
    - Their analysis can allow one to distinguish between the pMSSM and SUGRA models in several cases.

- **G.J. Gounaris, J. Layssac, F.M. Renard** (Phys.Rev.D77:093007,2008) have studied in detail helicity effects in SUSY with mSP4.

- **Anupama Atre, Yang Bai, and Estia Eichten**, "Supersymmetry at a Muon Collider" (Low Emitance Muon Collider Workshop, Fermilab)

Nature of Soft Breaking

1785 mSUGRA models out of 2 million point scan with Monte Carlo simulation

Nature of Soft Breaking

D. Feldman, Z. Liu and P. Nath, Phys. Rev. Lett. **99**, 251802 (2007)
D. Feldman, Z. Liu and P. Nath, JHEP **0804**, 054 (2008)

1785 mSUGRA models out of 2 million point scan with Monte Carlo simulation
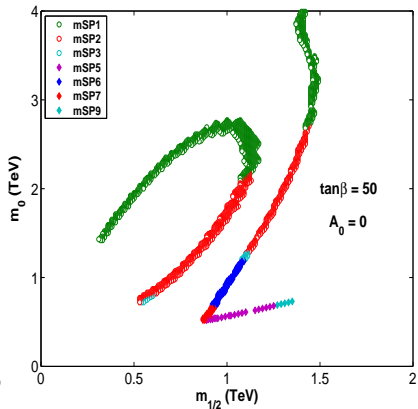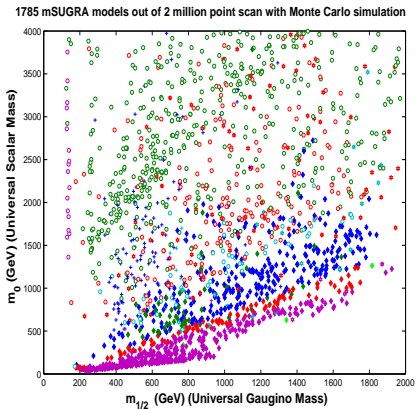
Experimental Constraints

- Relic Density (WMAP) $0.0855 < \Omega_{\widetilde{\chi}_1^0} h^2 < 0.1189 \ \ (2\sigma)$

- Exp: $\mathcal{B}r(b \to s\gamma) = (355 \pm 24^{+9}_{-10} \pm 3) \times 10^{-6}$
  HFAG, BABAR, Belle, and CLEO
  $\mathcal{B}r(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ at $O(\alpha_s^2)$
  M. Misiak et al., Phys. Rev. Lett. 98 (2007) 022002.

- $\mathcal{B}r(B_s \to \mu^+\mu^-) < 9 \times 10^{-6}$
  $\mathcal{B}r(B_s \to \mu^+\mu^-) < 1.2 \times 10^{-7}$ (95% CL) (Tevatron)

- $m_h > 100$ GeV

- $m_{\widetilde{\chi}_1^\pm} > 104.5$, $m_{\widetilde{t}_1} > 101.5$, $m_{\widetilde{\tau}_1} > 98.8$ (GeV) (LEP)

- $-11.4 \times 10^{-10} < g_\mu - 2 < 9.4 \times 10^{-9}$
  Brookhaven Muon (g-2) Collaboration

LHC Simulation Procedure

- micrOMEGAs[1] + SuSpect[2] [REWSB, RD, FC, Mass Limits]
- SUSY Les Houches Accord (SLHA) [3] [Spectrum & Mixings]
- PYTHIA 6.4.11 + PGS4 [MSEL=39] [4,5] [SUSY Production]
- Compare PYTHIA and PROSPINO[6] at LO
- TAUOLA [7] for τ decays with a DØ tested interface
- Level 1 (L1) triggers (CMS) and CMS Detector Parameters
- SM (QCD,$b\bar{b}$, $t\bar{t}$, DY, Z/W, $Z/W+$ jets, ZZ, WZ, WW)
- SMART (= SUSY Matrix Routine) [find mSPs, NUSPs etc..., Post Trigger Level Cuts, Count, Histogram, Analyze]
- $\mathrm{N_{SUSY}} > \mathrm{Max}\left\{5\sqrt{N_{SM}}, 10\right\}$ [Discovery Limit]

1 G. Belanger, F. Boudjema, A. Pukhov, A. Semenov
2 A.Djouadi, J.L. Kneur, G. Moultaka
3 B. Allanach et al. (SLHA Collaboration)
4 T. Sjostrand, S. Mrenna , P. Skands
5 John Conway et. al
6 W. Beenakker, R. Hopker, T. Plehn, M. Spira
7 S. Jadach, J. Kuhn, Z.Was

Post Trigger Level Cuts

- In an event, we only select photons, electrons, and muons that have transverse momentum $P_T^p > 10$ GeV and $|\eta^p| < 2.4$, $p = (\gamma, e, \mu)$.
- Taus which satisfy $P_T^\tau > 10$ GeV and $|\eta^\tau| < 2.0$ are selected.
- For hadronic jets, only those satisfying $P_T^j > 60$ GeV and $|\eta^j| < 3$ are selected.
- We require a large amount of missing transverse momentum, $P_T^{miss} > 200$ GeV.
- There are at least two jets that satisfy the P_T and η cuts.

Discriminating mSPs with Counting Signatures
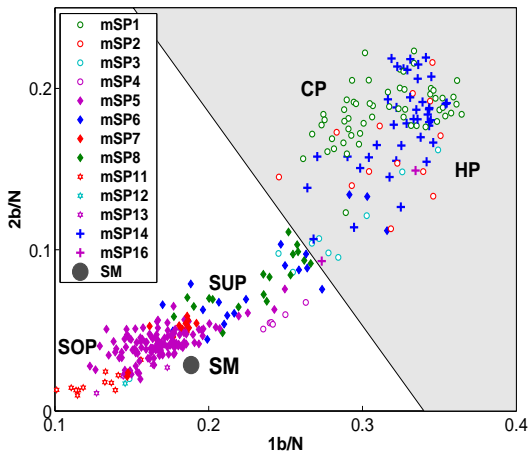
Figure: Separating out Mass Hierarchical Patterns with the LHC.

Discriminating mSPs with Counting Signatures
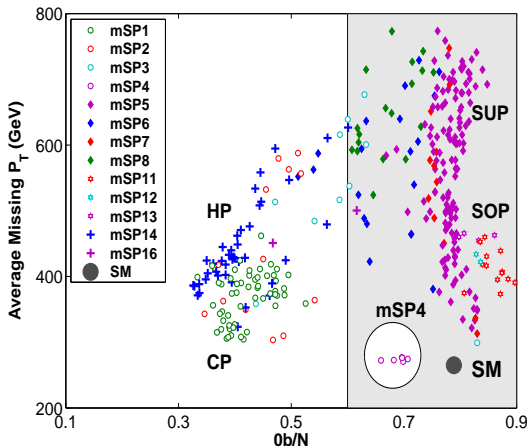
Figure: Pulling apart the mSPs with LHC Signatures - Binos , Higgsinos and Mixed Binos and Higgsinos, separate out.

D. Feldman, Z. Liu and P. Nath, JHEP **0804**, 054 (2008)
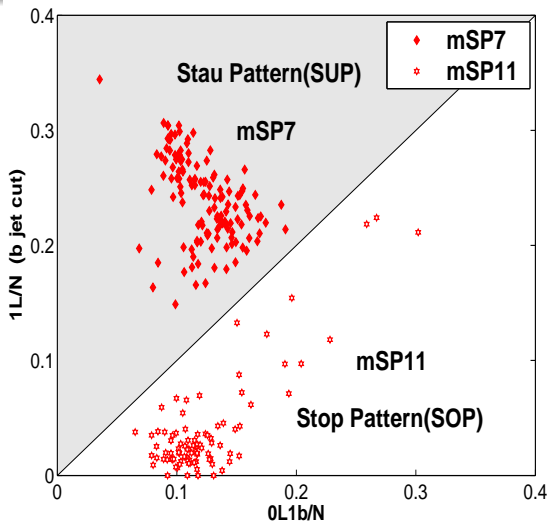
Missing Transverse Momentum
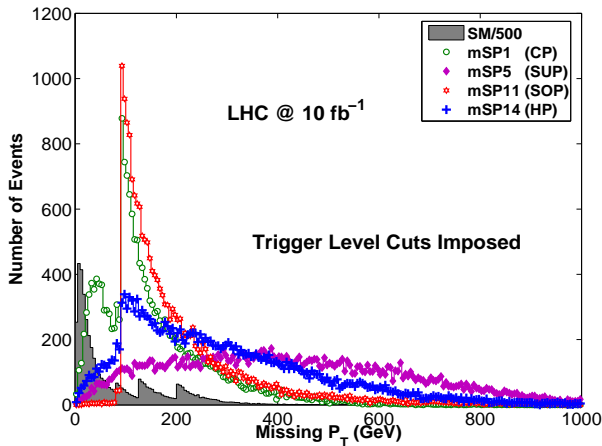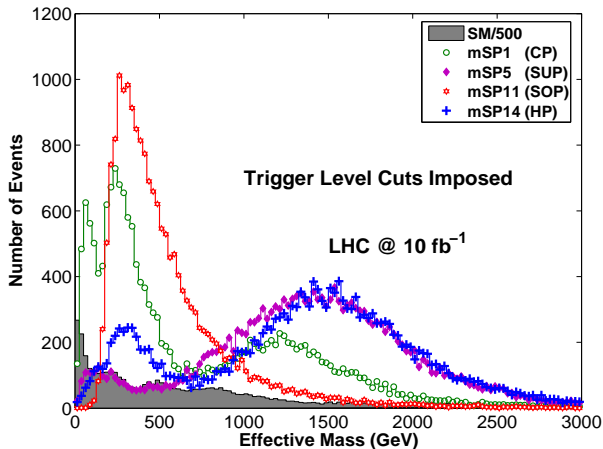
Figure: Effective mass distributions for the same mSUGRA models.

Effective Mass Distribution

Dilepton Invariant Mass Distribution

D. Feldman, Z. Liu and P. Nath, JHEP **0804**, 054 (2008)
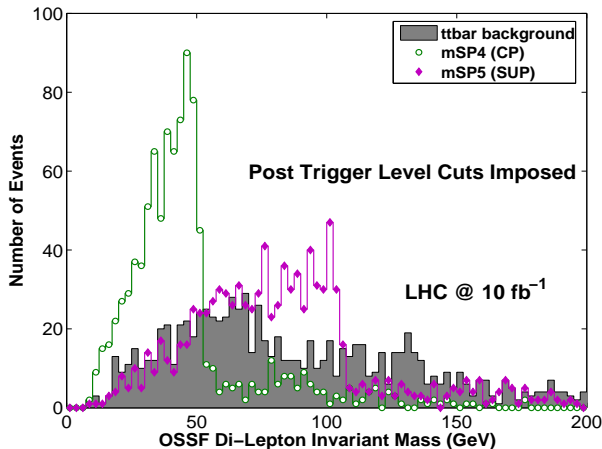
Tev and LHC Higgs production: Dominant Modes

5FNS

gluon fusion

$$gg \rightarrow \Phi$$

b quark annihilation

Dominant Modes If Requiring no high PT tagged b-jets

$$b\bar{b} \rightarrow \Phi$$

$h/H/A$
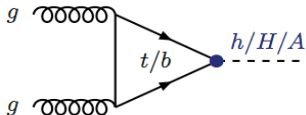
A. Djouadi hep-ph/0503173,
M. Spira, A. Djouadi, D. Graudenz,
P.M. Zerwas Nucl.Phys.B453:17-82,1995.

Example : Requiring one PT tagged b-jet (can reduce background)

Tevatron for LHC report: Higgs.
hep-ph/061217 and refs therein
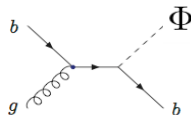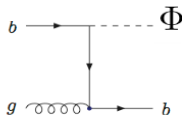
J.Campbell, R.K. Ellis, B. Kilgore, R. Harlander, F. Maltoni, Z. Sullivan,
S. Willenbrock, F. Maltoni, S. Dawson, C. Jackson, L. Reina, D.
Wackworth, S. Dittmaier, M. Kramer, A. Muck, T. Schluter

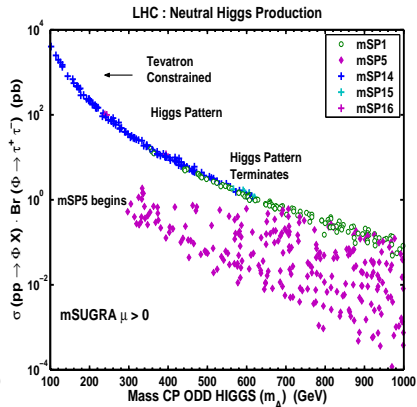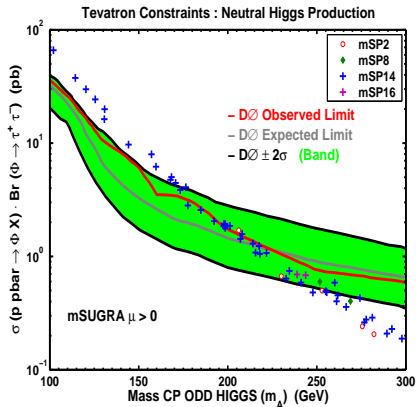## Higgs Production as a Pattern Discriminant

- For large $\tan \beta$ the b quark Yukawa couplings to $\Phi \equiv (h, H, A)$ are enhanced; dominant branchings are typically $(b\bar{b}, \tau\bar{\tau})$

- We find that the Tevatron data is beginning to constrain the HPs in 2τ mode.

- **M. Carena, S. Heinemeyer, C. Wagner, G. Weiglein**
  e-Print: hep-ph/0511023, Eur.Phys.J.C45:797-814,2006

$$\sigma_{p\bar{p}(p)} \cdot \mathrm{BR}(A \to 2\tau) \approx (\sigma_{gg,b\bar{b}\to\mathrm{Higgs}})_{\mathrm{SM}} \times \frac{\tan^2 \beta}{(1 + \delta_b)^2 + 9}$$
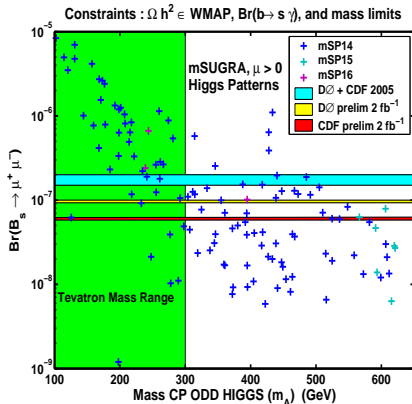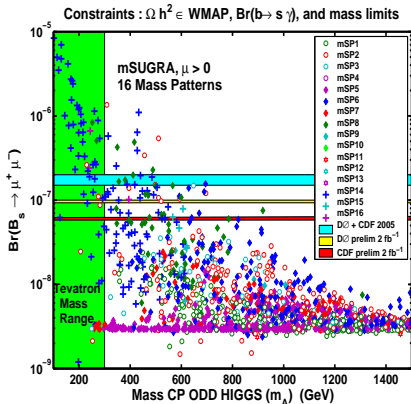
- δ_b arises from $\tilde{b} - \tilde{g}$ and $\tilde{t} - \tilde{h}$ loops and in the above, similar expressions for h, H production; above formula is a remarkable simplification and quite robust for large $\tan \beta$.

Constraints : $\Omega h^2 \in$ WMAP, Br(b $\rightarrow$ s γ), and mass limits

mSUGRA, $\mu > 0$
16 Mass Patterns

Constraints : $\Omega h^2 \in$ WMAP, Br(b $\rightarrow$ s γ), and mass limits

mSUGRA, $\mu > 0$
Higgs Patterns

Direct Detection of Dark Matter

mSUGRA, $\mu > 0$: mSP1–mSP16
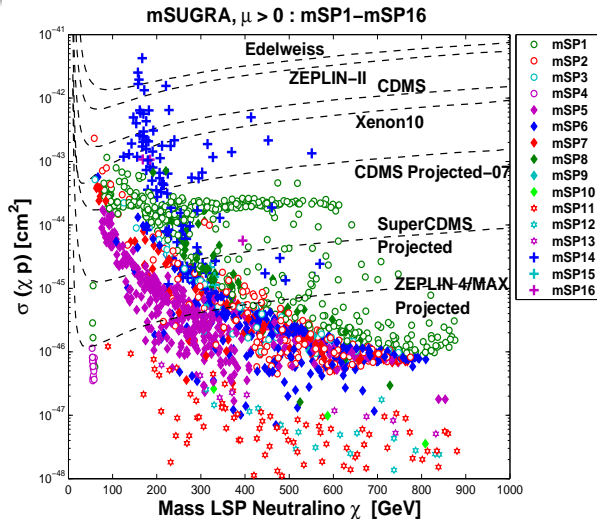
Direct Detection of Dark Matter
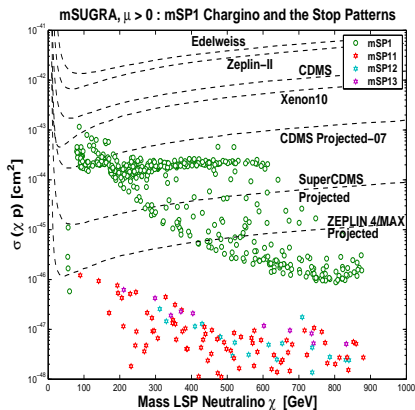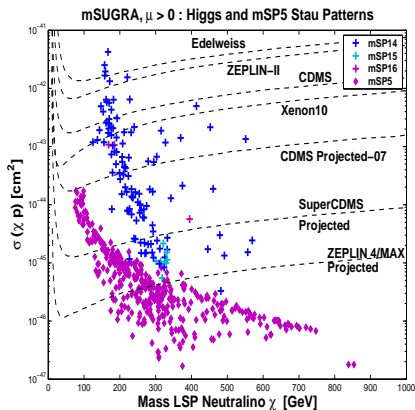
Central Points

- Knowledge of Sparticle Mass Hierarchies Play an important role in Sorting out SUSY; this new concept of the mSP/NUSP etc. becomes very relevant to understanding SUSY at Colliders and in Dark Matter experiments.

- Light Higgses are being constrained by CDF and DØ in high scale models and by CDMS and Xenon-10 experiments.

- Direct Detection of Dark Matter : Copious number of models sit on the Chargino Wall.

- Nature may be pointing towards light gauginos, they are the dominant pattern out of the landscape of possibilities. This is important in the context of a Linear Collider as well.

- Tevatron, LHC, and Dark Matter constraints; use in combination to sort out the underlying model.

Main Conclusions

- Knowledge of Sparticle Mass Hierarchies Play an important role in Sorting out SUSY; this new concept of the mSP/NUSP etc. becomes very relevant to understanding SUSY at Colliders and in Dark Matter experiments.

- Constraints are Converging: Tevatron Higgs Production, $B_s \to \mu^+ \mu^-$, Direct Detection of Dark Matter.

- Direct Detection of Dark Matter Acts as a Prism Separating out the Hierarchal Mass Patterns; Prospects are for dark matter detection are bright on the Chargino Wall.

- Tevatron, LHC, and Dark Matter Constraints, all must be investigated together.

- Connecting Colliders Signatures of new physics with Cosmological Signatures of new physics is perhaps one of the most important steps to sorting out the nature of physics beyond the SM.

What is the hidden sector?

- **Gravity**: Chamseddine, Arnowitt, Nath (1982), Hall, Lykken, Weinberg (1983)
- Candelas, Horowitz, Strominger, Witten (1985).
- Kaplunovsky, Louis (1993), Brignole, Ibanez, Munoz (1993) ...
- Several other susy breaking scenarios in the 90's (ex: Gauge and Anomaly)
- More recently the HS has resurfaced in various contexts : B. Kors and Nath (2004), Feldman, Liu, Nath (2006), Kumar and Wells (2006), Abel, Ringwald et al (2006) Strassler, Zurek et al (2006), Hooper, Russell, et al (2008) ...
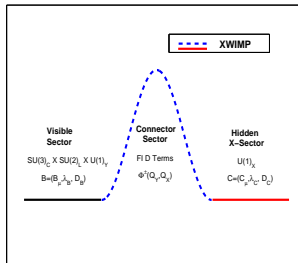
- Stueckelberg Extensions lead to 2 candidates for Dark Matter
  (1) mill-weak and (2) milli-charged

Stueckelberg Extensions

Kors, Nath PLB 2004, Feldman, Liu, Nath PRL 06, JHEP06, PRD 07

$$\Delta\mathcal{L}_{\text{StKM}} = -\frac{1}{4}C_{\mu\nu}C^{\mu\nu} - \frac{\delta}{2}B_{\mu\nu}C^{\mu\nu}$$
$$- \frac{1}{2}(M_1 C_\mu + M_2 B_\mu + \partial_\mu a)^2 + g_X J_X^\mu C_\mu + \mathcal{L}_{\text{g.f.}}$$

- Gauge Invariant under mixed $U(1)_{X,Y}$ transformations.

- SM fields are neutral under $U(1)_X$ and Hidden sectors fields are neutral under SM : $Q_{SM}|Hidden\rangle = Q_X|SM\rangle = 0$.

- $g_X J_X^\mu C_\mu \rightarrow \bar{\chi}\gamma^\mu[c_A A_\mu + c_Z Z_\mu + c_{Z'} Z'_\mu]\chi$.

- Mass mixings $\epsilon = M_2/M_1$ and Kinetic mixings δ distinctly different. In the limit $\epsilon \rightarrow 0$ there is no milli-charged coupling to photon. **Dirac χ is stable and can be Dark Matter**.

MSSM Extension

(Kors, Nath JHEP 2004,05, & Feldman, Kors, Nath PRD 2007)

$$\mathcal{L}_{\text{StMSSM}} = \mathcal{L}_{\text{St}} + \mathcal{L}_{\text{St,gkin}} + \mathcal{L}_{\text{St,matter}} + \mathcal{L}_{\text{MSSM}}$$

$$\begin{aligned}
\mathcal{L}_{\text{St}} &= -\frac{1}{2}(M_1 C_\mu + M_2 B_\mu + \partial_\mu a)^2 - \frac{1}{2}(\partial_\mu \rho)^2 - i\chi\sigma^\mu\partial_\mu\bar{\chi} \\
&\quad + \rho(M_1 D_C + M_2 D_B) + \left[\chi(M_1\lambda_C + M_2\lambda_B) + \text{h.c.}\right]
\end{aligned}$$

- $\widetilde{\chi}_1^0 = n_S\psi_S + n_X\lambda_X + \sum_{i=1}^{4} n_i\lambda_i$, couplings are suppressed due to EW constraints, **DM is extra-weak (Stino)**.

- New scalar ρ mixes with CP even Higgses.

- Both SM and MSSM extensions lead to a very narrow Z prime which can be quite light.
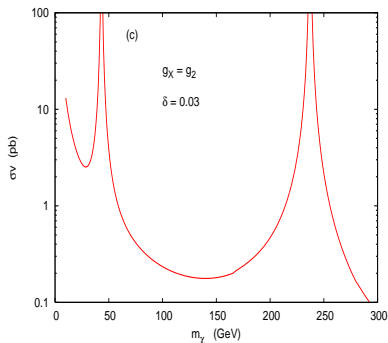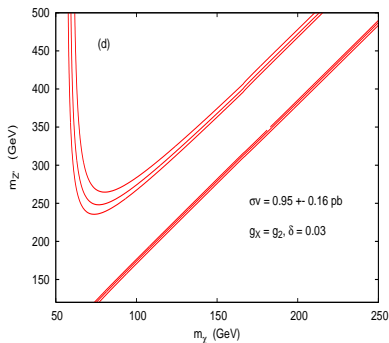
LEP Constraints on Stueckelberg Extensions,
D. Feldman, Z. Liu, Pran Nath : Phys.Rev.Lett.97:021801,2006

Table: The column labeled St Fit is an analysis for the input $\epsilon = 0.06$, $\delta = 0.03$, and $M_1 = 200$ GeV. In the last column PULL is defined by $(\text{Experiment} - \text{FIT})/\Delta$, and $\chi^2 = \sum \text{PULL}^2$.

| Quantity	Experiment $\pm \Delta$	LEP FIT	St FIT	LEP PULL	St PULL
Γ_Z [GeV]	2.4952 ± 0.0023	2.4956	2.4956	-0.17	-0.17
σ_{had} [nb]	41.541 ± 0.037	41.476	41.469	1.76	1.95
R_e	20.804 ± 0.050	20.744	20.750	1.20	1.08
R_μ	20.785 ± 0.033	20.745	20.750	1.21	1.06
R_τ	20.764 ± 0.045	20.792	20.796	-0.62	-0.71
R_b	0.21643 ± 0.00072	0.21583	0.21576	0.83	0.93
R_c	0.1686 ± 0.0047	0.17225	0.17111	-0.78	-0.53
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01627	0.01633	-0.71	-0.73
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013	0.01627	0.01633	0.48	0.44
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017	0.01627	0.01633	1.49	1.45
$A_{FB}^{(0,b)}$	0.0991 ± 0.0016	0.10324	0.10344	-2.59	-2.71
$A_{FB}^{(0,c)}$	0.0708 ± 0.0035	0.07378	0.07394	-0.85	-0.90
$A_{FB}^{(0,s)}$	0.098 ± 0.011	0.10335	0.10355	-0.49	-0.50
A_e	0.1515 ± 0.0019	0.1473	0.1476	2.21	2.05
A_μ	0.142 ± 0.015	0.1473	0.1476	-0.35	-0.37
A_τ	0.143 ± 0.004	0.1473	0.1476	-1.08	-1.15
A_b	0.923 ± 0.020	0.93462	0.93464	-0.58	-0.58
A_c	0.671 ± 0.027	0.66798	0.66812	0.11	0.11
A_s	0.895 ± 0.091	0.93569	0.93571	-0.45	-0.45
				$\chi^2 = 25.0$	$\chi^2 = 25.2$

Satisfaction of Relic Density in the Stueckelberg Model

Kingman Cheung and T.C. Yuan, JHEP 0703:120,2007

Satisfaction of Relic Density and Tevatron Constraints on the Stueckelberg Model

D. Feldman, Z. Liu, Pran Nath **Phys.Rev.D75:115001,2007**
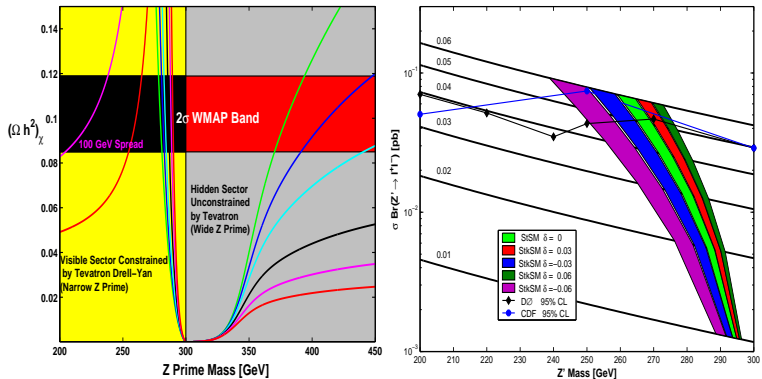
Figure: Stueckelberg Extensions: Satisfying WMAP and Producing a light Z prime that is detectable at the Tevatron.

Primary Positrons from DM Annihilations in the Halo

$$
\Phi_{e^+} = B_{e^+} \frac{v_{e^+}}{4\pi b(E)} \eta \left(\frac{\rho_\odot}{M_\chi} \right)^2 \int_E^{M_\chi} dE' \; f_{\text{inj}}(E') \cdot I\left(\lambda_D(E, E') \right)
$$

- $f_{\text{inj}}(E') = \sum_F \langle \sigma v \rangle_{F,\text{Halo}} (dN/dE')_F$
- In St model $\chi\bar{\chi} \to Z' \to f\bar{f}$ is strong for $2M_\chi < M_{Z'}$
- $\eta = \frac{1}{(2,4)}$ for (Majorana,Dirac) $(N(N-1)/2, (N/2)^2)$ in limit of large N where for the Dirac DM case symmetric contributions from the χ and $\bar{\chi}$ are assumed
- $\rho_\odot$ is the (local) DM Density
- $b(E)$ loss factor due to particles passing through the magnetic fields and loss due to radiation, and bkgd. scattering ($b(E) \sim (E/\text{GeV})^2/10^{16}$ [GeV/s]).
- $I\left(\lambda_D(E, E')\right)$ encodes the profile and diffusion model
- B_{e^+} is a 'boost' factor (sometimes called 'fd' in the literature).

Boost in the $\langle \sigma v \rangle$ from the Hidden Sector Pole

Feldman, Liu, Nath: arXiv:0810.5762 [hep-ph].
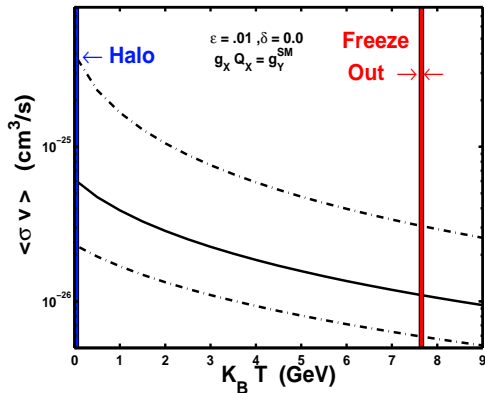
Halo/Diffusion Models

$$\rho(r) = \frac{\rho_\odot}{(r/r_c)^\gamma [1 + (r/r_c)^\alpha]^{(\beta-\gamma)/\alpha}}.$$

Characteristics of two halo models.

| Halo model	α	β	γ	r_c (kpc)
Navarro, Frenk, White	1	3	1	20
Moore	1.5	3	1.5	28

Integral over the halo function depends on diffusion parameters and length of Cylinder δ, K_0, $2L$. Some preferred values are

| Model	δ	K_0 [kpc^2/Myr]	L [kpc]
MIN	0.85	0.0016	1
MED	0.70	0.0112	4
MAX	0.46	0.0765	15

- I. V. Moskalenko, A. W. Strong, Astrophys.J.493:694-707,1998 (secondaries)
- E. Baltz, J. Edsjo, Phys.Rev.D59:023511,1999 (detailed early work, basis of DS)
- D. Hooper, J. Silk, Phys.Rev.D71:083503,2005 (detailed early work; Boost well defined - inhomogeneity of the local dark DM ρ)
- J. Hisano, S. Matsumoto, O. Saito, M. Senami, Phys.Rev.D73:055004,2006 (detailed analytical work with fits to Dibosons FFs)
- T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati,Phys.Rev.D77:063527,2008 (fits of profiles and analytical work)
- M. Cirelli , R. Franceschini, A. Strumia, Nucl.Phys.B800:204-220,2008 (detailed analysis and analytical work)
- D. Hooper, J. Hall, P. Blasi, P. D. Serpico, arXiv:0810.1527 & arXiv:0811.3362 (spinning, magnetized neutron stars may explain PAMELA excess)

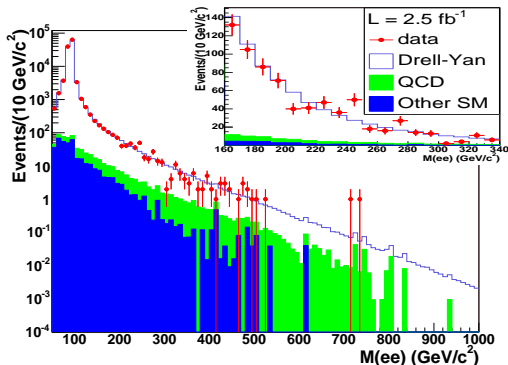## PAMELA positron excess in Stueckelberg extension of SM

Feldman, Liu, Nath: arXiv:0810.5762 [hep-ph].
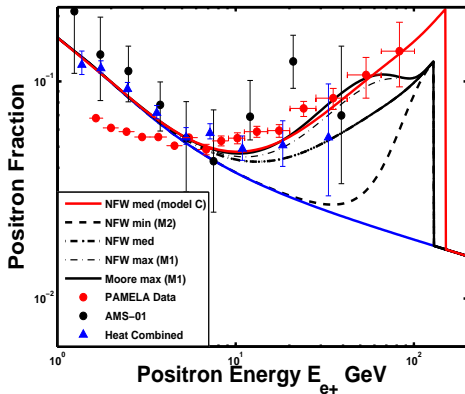
PAMELA antiprotons
FLN, work in Progress
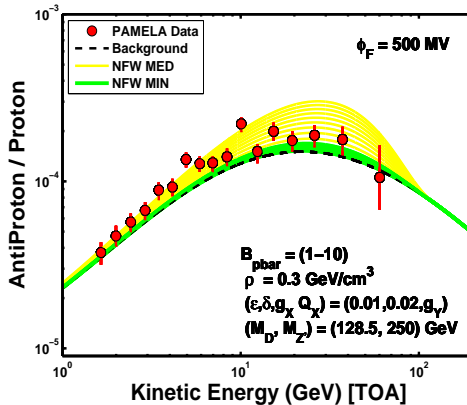
CDF Run II Preliminary

- "The most significant region of excess of data over background occurs for an e^+e^- invariant mass window of $240 \text{GeV}/c^2$, and is 3.8 standard deviations above the standard model prediction." (CDF II Exotics Group Public Page; public note: CDF/PUB/EXOTIC/PUBLIC/9160)

Central Results

- Annihilation of hidden sector dark matter close to the Stueckelberg Z' pole can satisfy the relic density consistent with WMAP constraints.

- It can generate a positron fraction excess compatible with the AMS-01, HEAT and the more accurate PAMELA data.

- Further tests of the model can come at the Tevatron or LHC via discovery of a narrow Z' with a mass $M_{Z'} \sim 2M_D$ and by an analysis of its branching ratios.

- The Current CDF data in the Drell-Yan Di-lepton channel may be hinting at new physics, though corroboration from D0 is needed before anyone jumps the gun.

Main Conclusions

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